15-745 Introduction

Seth Copen Goldstein
Seth@cs.cmu.Edu
CMU

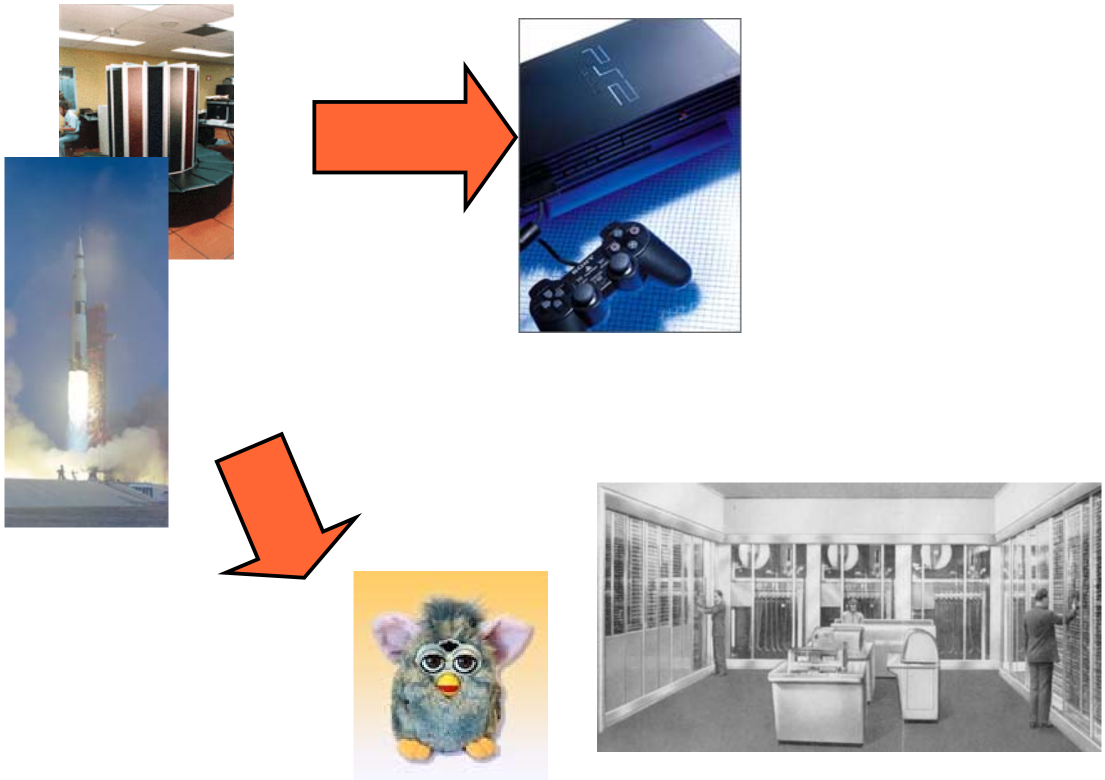
Based in part on slides by
Todd Mowry and Michael Voss

Introduction

- Why study compilers?
- Administriva
- Structure of a Compiler
- Optimization Example

Reference: Muchnick 1.3-1.5

Moore's Law



Moore's Law

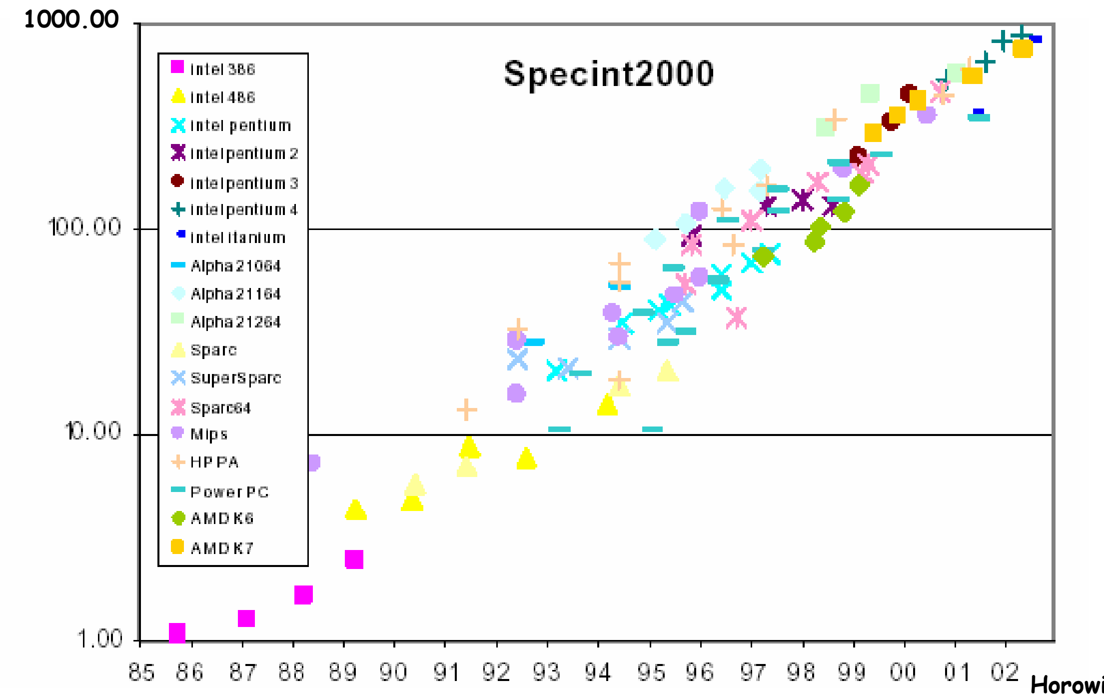
Imagine: Computers that

Imagining it is hard enough, achieving it requires a rethink of the entire tool chain.

What is Behind Moore's Law?

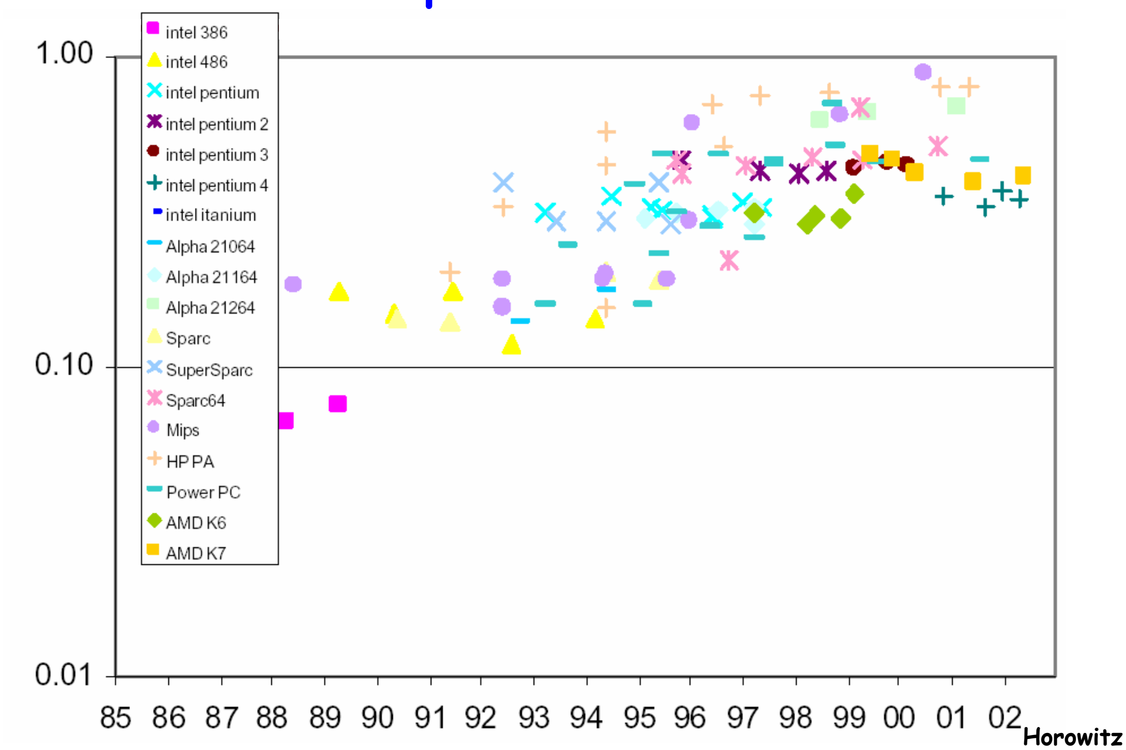
- A lot of hard work!
- Two most important tools:
  - Parallelism
    - Bit-level
    - Pipeline
    - Function unit
    - Multi-core
  - Locality

Performance: Ops/Clk * Clks/Sec

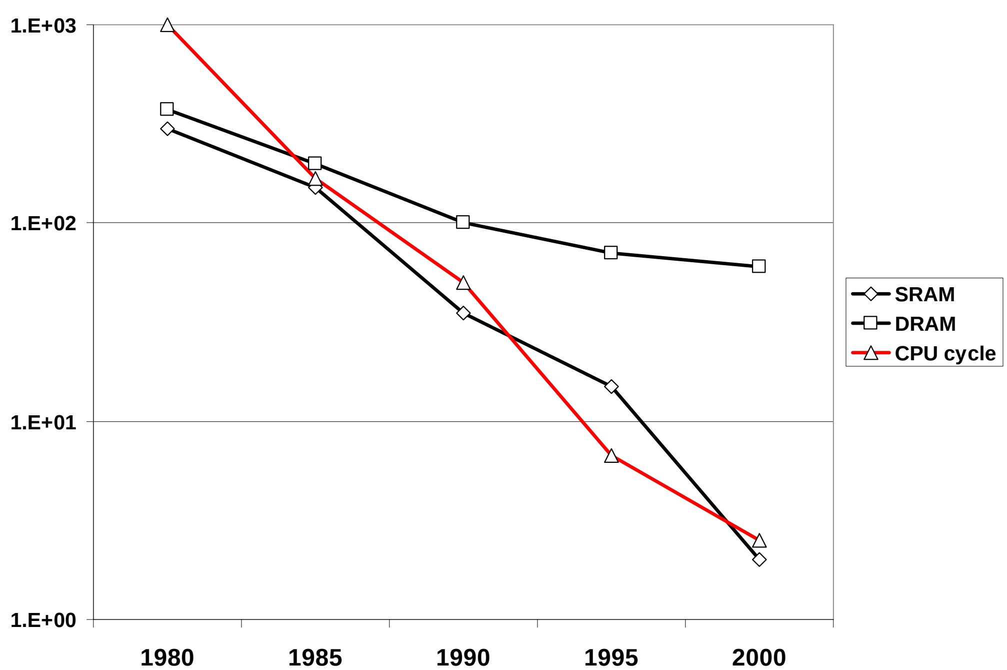


Horowitz

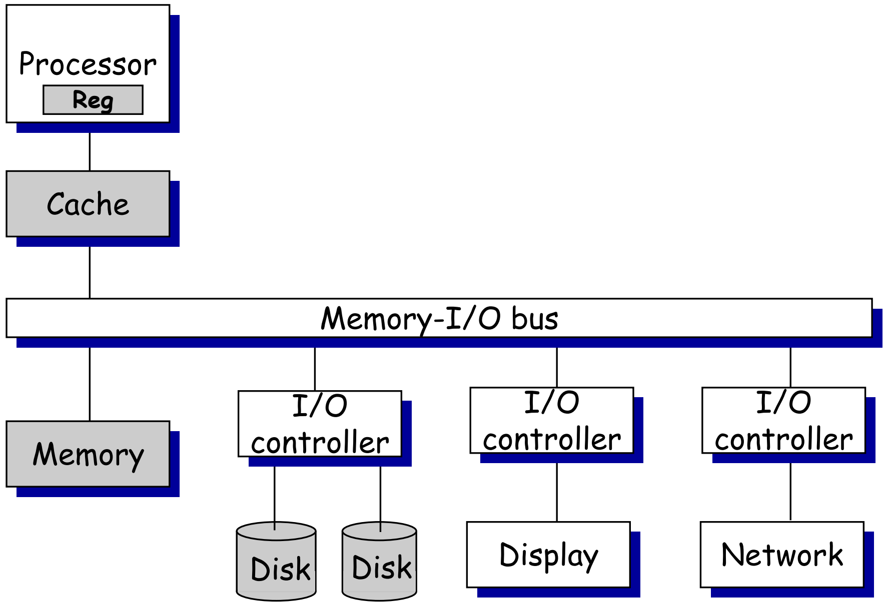
SpecInt/Mhz



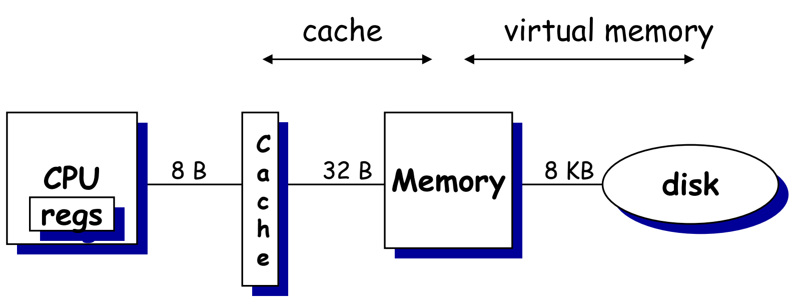
Another View of Moore's Law



The Computer System



The Memory Hierarchy



	Register	Cache	Memory	Disk Memory
size:	200 B	32 KB/4MB	128 MB	20 GB
speed:	3 ns	6 ns	60 ns	8 ms
$/Mbyte:		$100/MB	$.30/MB	$0.005/MB
block size:	8 B	32 B	8 KB	

larger, slower, cheaper →

Compiler Writer's Job

- Improve locality
- Increase parallelism
- Tolerate latency
- Reduce power

Why study compilers

- They are really amazing
- Combines theory & practice
  - CS is about abstraction
    - Primary abstraction: programming language
    - Compiler lowers PL to ISA (or further!)
  - Compiler is a big system
- Crucial for performance
  - especially for modern processors
  - practically part of the architecture
- I bet: Everyone will write a compiler

Why study compilers

- They are really amazing
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  - CS is about abstraction
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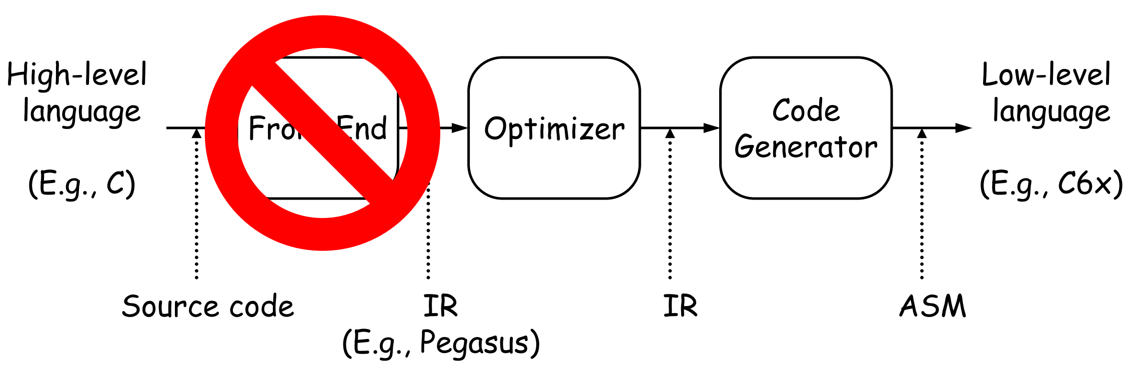
- Crucial for performance
  - especially for modern processors
  - practically part of the architecture
- I bet: Everyone will write a compiler

What this course is about



- Theory and practice of modern optimizing compilers
  - No lexing or parsing
  - Focus on IR, back-end, optimizations
- Internals of today's (and tomorrow's) compilers
- Building a real compiler for embedded processor

Prerequisites

- 211 & 213 or the equivalent
- Parts of 411 or the equivalent
  - Basic compiler data structures
  - Frames, calling conventions, def-use chains, etc.
  - Don't really care about front-end
- Proficient in C/C++ programming
- Basic understanding of architecture

My Expectations

- You have the prerequisites
  - If not come see tim or me asap
- 4 assignments + a project
- Class participation
  - THIS IS A MUST!
  - Read text/papers before class
  - Attendance is essentially mandatory

Grading

- Class participation ~20%
  - Throughout the semester
  - During paper presentations
  - Project presentations
- Labs ~20%
- Project ~30%
- Midterm ~15%
- Final ~15%

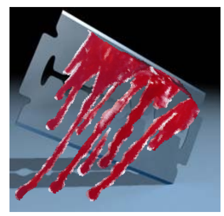
Grading

- Class participation ~20%
  - Throughout the semester
  - During paper presentations
  - Project presentations
- Labs ~25%
- Project ~35%
- Midterm ~20%

Labs

- ADCE & CCP in Pegasus
- Global register allocation
- Global Code Scheduling
- Profile-based optimization

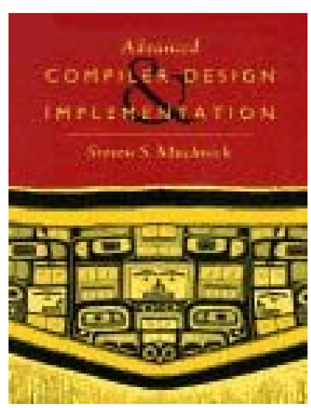
- All labs and the final project will be done in a state-of-the-art research compiler.



The Text

- Steven S. Muchnick, Advanced Compiler Design and Implementation. Morgan Kaufmann Publishers, 1997

- Papers will be assigned



Before we get too bored

- More admin at the end, but first …
- What exactly is an optimizing compiler?
  - An optimizing compiler transforms a program into an equivalent, but "better" form.
  - What is equivalent?
  - What is better?

Full Employment Theorem

- No such thing as "The optimizing compiler"
  - Why not?
- There is always a better optimizing compiler, but …
  - Compiler must preserve correctness
  - On average improve X, where X is:
    - Performance
    - Power
    - …
  - Finish in your lifetime

How might performance be improved?

$$\text{execution time} = \sum_{\text{instructions}} \text{cycles per instruction}$$

- Reduce the number of instructions
- Replace "expensive" instructs with "cheap" ones
- Reduce memory cost
  - Improve locality
  - Reduce # of memory operations
- Increase parallelism

Ingredients to a compiler opt

- Identify opportunity
  - Avail in many programs
  - Occurs in key areas (what are these?)
  - Amenable to "efficient" algorithm
- Formulate Problem
- Pick a Representation
- Develop an Analysis
  - Detect when legal
  - And desirable
- Implement Code Transformation
- Evaluate (and repeat!)

Examples of Optimizations

- Machine Independent
  - Algebraic simplification
  - Constant propagation
  - Constant folding
  - Common Sub-expression elimination
  - Dead Code elimination
  - Loop Invariant code motion
  - Induction variable elimination
- Machine Dependent
  - Jump optimization
  - Reg allocation
  - Scheduling
  - Strength reduction
  - Loop permutations

Really Powerful Opts we won't do

- How to optimize:

```
Sumfrom1toN(int max) {
  sum = 0;
  for (i=1; i<=max; i++) sum+=i;
  return sum;
}
```

Really Powerful Opts we won't do

- How to optimize:

```
Sumfrom1toN(int max) {
  sum = 0;
  for (i=1; i<=max; i++) sum+=i;
  return sum;
}
```

- What we should, but won't do:

```
inline sumfrom1toN(int max) {
  return max > 0 ?
   ((max+max*max)>>1) : 0;
}
```


Algebraic Simplifications

a*1; ⇒ a

a/1; ⇒ a

a*0; ⇒ 0

a+0; ⇒ a

a-0; ⇒ a

a = b + 1
c = a - 1 ⇒ c = b

Use algebraic identities to simplify computations

Jump Optimizations

```
   cmp d0,d1              cmp d0,d1
   beq  L1
   bra  L2                bne  L2
L1:        :      ⇒    L1:        :
           :                      :
L2:        :           L2:        :
      :                      :
```

Simplify jump and branch instructions.

Constant Propagation

```
a = 5;                              a = 5;
b = 3;                              b = 3;
   :                                   :
   :                                   :
n = a + b;                    ⇒     n = 5 + 3;
for (i = 0; i<n; ++i)               for (i = 0; i<n; ++i)
{                                   {
      :                                   :
}                                   }
```

If the compiler can determine that the values of **a** and **b** are constants, then it can replace the variable uses with constant values.

Constant Folding

```
        :
        :
        :
        :
n =   8   ;
for (i = 0 ; i < 8 ; ++i) {
        :
}
```

- The compiler evaluates an expression (at compile time) and inserts the result in the code.
- Can lead to further optimization opportunities; esp. constant propagation.

Common Subexpression Elimination (CSE)

```
a = c*d;                      a = c*d;
      :                             :
      :          ⇒                  :
d = (c*d + t) * u             d = (a + t) * u
```

If the compiler can determine that:

- an expression was previously computed
- and that the values of its variables have not changed since the previous computation,

Then, the compiler can use the previously computed value.

Strength Reduction

- On some processors, the cost of an addition is less than the cost of multiplication.
- The compiler can replace expensive multiplication instructions by less expensive ones.

```
c = b * 2;

move $2000, d0
muls  #2, d0
move d0, $3000
```

```
c = b + b;

move $2000, d0
add   d0, d0
move d0, $3000
```

```
c = lsh(b);

move $2000, d0
lsl      #1, d0
move d0, $3000
```

```
c = -1*b;

move $2000, d0
muls  #-1,d0
move d0, $3000
```

```
c = negative(b);

move $2000, d0
neg   d0
move d0, $3000
```


Dead Code Elimination

```
debug = False;
     :
     :
if (debug) {
    :
    :
}
a = f(b);
```

If the compiler can determine that code will never be executed or that the result of a computation will never be used, then it can eliminate the code or the computation.

Loop Invariant Code Motion

```
for (i=0; i<100 ;  ++i) {
  for (j=0; j<100 ; ++j) {
    for (k=0 ; k<100 ; ++k)
    {
       a[i][j][k] = i*j*k;
    }
  }
}
```

```
for (i=0; i<100 ;  ++i) {
  for (j=0; j<100 ; ++j) {
    t1 = a[i][j];
    t2 = i*j;
    for (k=0 ; k<100 ; ++k)
    {
       t1[k] = t2*k;
    }
  }
}
```

- Loop invariant: expression evaluates to the same value each iteration of the loop.
- Code motion: move loop invariant outside loop.
- Very important because inner-most loop executes most frequently.

Loop Invariant Code Motion

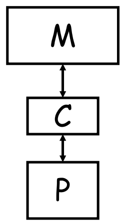
```
int *a;
int n;
    :
    :
scanf("%d", &n);
for (i=0; i<n ;  ++i) {
 for (j=0; j<n ; ++j) {
  for (k=0 ; k<n ; ++k)
  {
    f = q/p;
    a[i][j][k] = f*i*j*k;
  }
 }
}
```

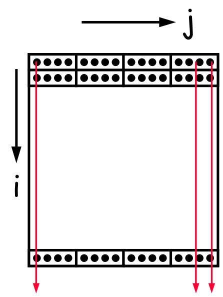
```
int *a;
int n;
    :
    :
scanf("%d", &n);
f = q/p;
for (i=0; i<n ;  ++i) {
 for (j=0; j<n ; ++j) {
  t1 = a[i][j];
  t2 = i*j;
  for (k=0 ; k<n ; ++k)
  {
     t1[k] = f*t2*k;
  }
 }
}
```

Oooops!!!!!

Cache Optimizations

```
for (j=0; j<n ;  ++j) {
   for (i=0; i<n ; ++i) {
         x += a[i][j];
   }
}
```



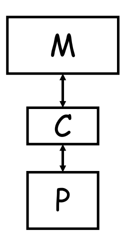


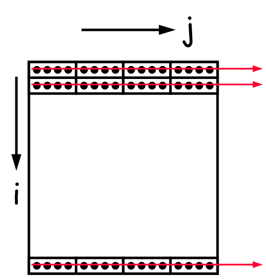
Loop permutation changes the order of the loops to improve the spatial locality of a program.

Cache Optimizations

```
for (j=0; j<n ;  ++j) {
   for (i=0; i<n ; ++i) {
         x += a[i][j];
   }
}
```

```
for (i=0; i<n ;  ++i) {
   for (j=0; j<n ; ++j) {
         x += a[i][j];
   }
}
```



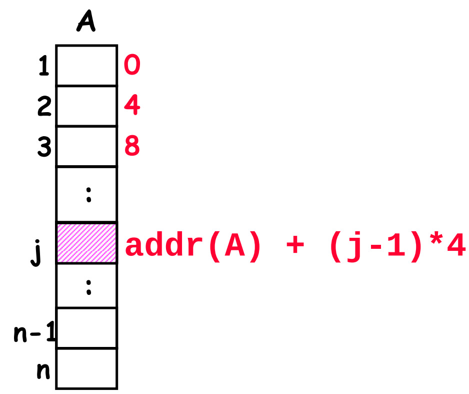


Loop permutation changes the order of the loops to improve the spatial locality of a program.

Example

A program that sorts 4-byte elements in an n-element array of integers A[1..n] using bubblesort.

```
for (i=n-1; i >= 1 ; --i) {
    for (j = 1; j <= i ; ++j) {
        if (A[j] > A[j+1]) {
            temp = A[j];
            A[j] = A[j+1];
            A[j+1] = temp;
        }
    }
}
// i and j are not used later
```

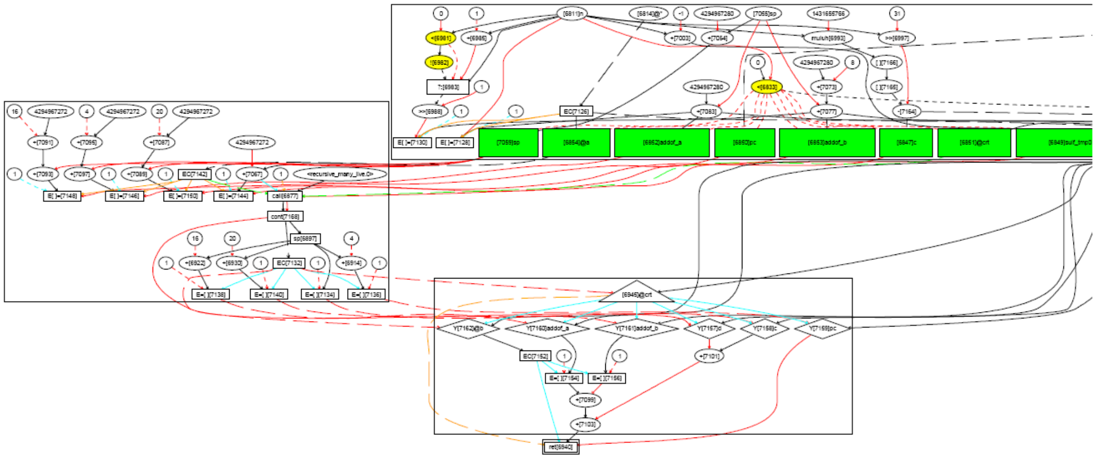


A Generated IR

```
for i {        i = n-1
           S5: if i < 1 goto Exit
for j {        j = 1
           S4: if j > i goto S2
A[j] {         t1 = j-1
               t2 = 4*t1
               t3 = [A+t2]
A[j+1] {       t4 = j+1
               t5 = t4-1
               t6 = 4*t5
if {           t7 = [A+t6]
               if t3 <= t7 goto S3
A[j] {         t8 = j-1
               t9 = 4*t8
temp= A[j] {   temp = [A+t9]
```

```
t10 = j+1          }
t11 = t10-1        } A[j+1]
t12 = 4*t11        }
t13 = [A+t12]      }
t14 = j-1          } A[j]
t15 = 4*t14
[A+t15] = t13      } A[j]=A[j+1]
t16 = j+1          }
t17 = t16-1        } A[j+1]
t18 = 4*t17        }
[A+t18] = temp     } A[j+1]=temp
S3: j = j+1        } for j
    goto S4
S2: i = i-1        } for i
    goto S5
Exit:
```

Another generated IR



Optimizations I - Algebraic Simplifications

```
     i = n-1
S5:  if i < 1 goto Exit
     j = 1
S4:  if j > i goto S2
     t1 = j-1
     t2 = 4*t1
     t3 = [A+t2]
     t4 = j+1
     t5 = t4-1
     t6 = 4*t5
     t7 = [A+t6]
     if t3 <= t7 goto S3
     t8 = j-1
     t9 = 4*t8
     temp = [A+t9]
```

```
     t10 = j+1
     t11 = t10-1
     t12 = 4*t11
     t13 = [A+t12]

     t14 = j-1
     t15 = 4*t14
     [A+t15] = t13
     t16 = j+1
     t17 = t16-1
     t18 = 4*t17
     [A+t18] =
temp
S3:  j = j+1
     goto S4
S2:  i = i-1
     goto S5
Exit:
```

```
t12 = 4*j
```

```
t18 = 4*j
```

```
t6 = 4*j
```

Optimizations II - CSE

```
     i = n-1
S5:  if i < 1 goto Exit
     j = 1
S4:  if j > i goto S2
     t1 = j-1
     t2 = 4*t1
     t3 = [A+t2]
     t6 = 4*j
     t7 = [A+t6]
     if t3 <= t7 goto S3
     t8 = j-1
     t9 = 4*t8
     temp = [A+t9]
     t12 = 4*j
     t13 = [A+t12]
     t14 = j-1
     t15 = 4*t14
     [A+t15] = t13
     t18 = 4*j
     [A+t18] = temp
S3:  j = j+1
     goto S4
S2:  i = i-1
     goto S5
Exit:
```

```
t14 = t1
t8 = t1
```


Optimizations II - CSE

```
     i = n-1
S5:  if i < 1 goto Exit
     j = 1
S4:  if j > i goto S2
     t1 = j-1
     t2 = 4*t1
     t3 = [A+t2]
     t6 = 4*j
     t7 = [A+t6]
     if t3 <= t7 goto S3
     t8 = t1
     t9 = 4*t8
     temp = [A+t9]
     t12 = 4*j
     t13 = [A+t12]
     t14 = t1
     t15 = 4*t14
     [A+t15] = t13
     t18 = 4*j
     [A+t18] = temp
S3:  j = j+1
     goto S4
S2:  i = i-1
     goto S5
Exit:
```

```
t12 = t6
t18 = t6
```

Optimizations III - Copy Propagation

```
     i = n-1
S5:  if i < 1 goto Exit
     j = 1
S4:  if j > i goto S2
     t1 = j-1
     t2 = 4*t1
     t3 = [A+t2]
     t6 = 4*j
     t7 = [A+t6]
     if t3 <= t7 goto S3
     t8 = t1
     t9 = 4*t8
     temp = [A+t9]
     t12 = t6
     t13 = [A+t12]
     t14 = t1
     t15 = 4*t14
     [A+t15] = t13
     t18 = t6
     [A+t18] = temp
S3:  j = j+1
     goto S4
S2:  i = i-1
     goto S5
Exit
```

```
t13 = [A+t6]
t15 = 4*t1
[A+t6] = temp
t9 = 4*t1
```


Optimizations IV - CSE (2)

```
     i = n-1
S5:  if i < 1 goto Exit
     j = 1
S4:  if j > i goto S2
     t1 = j-1
     t2 = 4*t1
     t3 = [A+t2]
     t6 = 4*j
     t7 = [A+t6]
     if t3 <= t7 goto S3
     t9 = 4*t1
     temp = [A+t9]
     t13 = [A+t6]
     t15 = 4*t1
     [A+t15] = t13
     [A+t6] = temp
S3:  j = j+1
     goto S4
S2:  i = i-1
     goto S5
Exit:
```

```
t13 = t7
t15 = t2
t9 = t2
```

Optimizations V - Copy Propagation (2)

```
     i = n-1                                      t13 = t7
S5:  if i < 1 goto Exit       [A+t2] = t7  <--    t15 = t2
     j = 1                                        [A+t15] = t13
S4:  if j > i goto S2                             [A+t6] = temp
     t1 = j-1
     t2 = 4*t1                               S3:  j = j+1
     t3 = [A+t2]                                  goto S4
     t6 = 4*j                                S2:  i = i-1
     t7 = [A+t6]                                  goto S5
     if t3 <= t7 goto S3                     Exit:
     t9 = t2
     temp = [A+t9]      -->   temp = [A+t2]
```


Optimization VI - CSE (3)

```
     i = n-1                                      [A+t2] = t7
S5:  if i < 1 goto Exit                           [A+t6] = temp
     j = 1
S4:  if j > i goto S2                        S3:  j = j+1
     t1 = j-1                                     goto S4
     t2 = 4*t1                               S2:  i = i-1
     t3 = [A+t2]                                  goto S5
     t6 = 4*j                 temp = t3      Exit:
     t7 = [A+t6]
     if t3 <= t7 goto S3
     temp = [A+t2]      -->   temp = t3
```

Optimization VII - Copy Propagation (3)

```
      i = n-1
S5:   if i < 1 goto Exit
      j = 1
S4:   if j > i goto S2
      t1 = j-1
      t2 = 4*t1
      t3 = [A+t2]
      t6 = 4*j
      t7 = [A+t6]
      if t3 <= t7 goto S3
      temp = [t3]
      [A+t2] = t7
      [A+t6] = temp
      [A+t6] = [t3]
S3:   j = j+1
      goto S4
S2:   i = i-1
      goto S5
Exit:
```


Optimizations VIII - IVE & Strength Reduction

```
      i = n-1
S5:   if i < 1 goto Exit
      j = 1
S4:   if j > i goto S2
      t1 = j-1
      t2 = 4*t1
      t3 = [A+t2]
      t6 = 4*j
      t7 = [A+t6]
      if t3 <= t7 goto S3
      [A+t2] = t7
      [A+t6] = t3
S3:   j = j+1
      goto S4
S2:   i = i-1
      goto S5
Exit:
```

Optimizations VIII - IVE & Strength Reduction

```
     i = n-1
S5:  if i < 1 goto Exit
     j = 1
S4:  if j > i goto S2
     t1 = j-1
     t2 = 4*t1
     t3 = [A+t2]
     t6 = 4*j
     t7 = [A+t6]
     if t3 <= t7 goto S3
     [A+t2] = t7
     [A+t6] = t3
S3:  j = j+1
     goto S4
S2:  i = i-1
     goto S5
Exit:
```

Loop Invariant Code Motion...

```
     i = n-1
S5:  if i < 1 goto Exit
     t2 = 0
     t6 = 4
S4:  t19 = 4*i
     if t6 > t19 goto S2
     t3 = [A+t2]

     t7 = [A+t6]
     if t3 <= t7 goto S3
     [A+t2] = t7
     [A+t6] = t3
S3:  t2 = t2+4
     t6 = t6+4
     goto S4
S2:  i = i-1
     goto S5
Exit:
```


Done?

```
     i = n-1
S5:  if i < 1 goto Exit
     t2 = 0
     t6 = 4
S4:  t19 = 4*i
     if t6 > t19 goto S2
     t3 = [A+t2]
     t7 = [A+t6]
     if t3 <= t7 goto S3
     [A+t2] = t7
     [A+t6] = t3
S3:  t2 = t2+4
     t6 = t6+4
     goto S4
S2:  i = i-1
     goto S5
Exit:
```

t19 = i*4

t19 < 4

[A-4+t6]

t19 = t19-4

Done?

```
    i = n-1
    t19 = i*4
S5: if t19 < 4 goto Exit
    t6 = 4
S4: if t6 > t19 goto S2
    t3 = [A+t6-4]
    t7 = [A+t6]
    if t3 <= t7 goto S3
    [A+t6-4] = t7
    [A+t6] = t3
S3: t6 = t6+4
    goto S4
S2: t19 = t19 - 4
    goto S5
Exit:
```

Eliminate mult,
Use double load (if aligned?)
Unroll?
Eliminate jmp
...

Done For Now.

```
    i = n-1
    t19 = i<<2
    if t19 < 4 goto Exit
S5: t6 = 4
    if t6 > t19 goto S2
S4: t3 = [A+t6-4]
    t7 = [A+t6]
    if t3 <= t7 goto S3
    [A+t6-4] = t7
    [A+t6] = t3
S3: t6 = t6+4
    if t6 <= t19 goto s4
S2: t19 = t19 - 4
    if t19 >= 4 goto s5
Exit:
```

Inner loop: 7 instructions
4 mem ops
2 branches
1 addition

Original inner loop: 25 instructi
6 mem ops
3 branches
10 addition
6 multiplication

Course Schedule

- www.cs.cmu.edu/afs/cs/academic/class/15745-s07h/www/
- The Web site is a vital resource
- Also, class newsgroup
- (And, of course us too)

Course Staff

- Tim Callahan www..../~tcal
- Seth Goldstein www..../~seth
- Mahim Mishra www..../~mishra
- Marilyn Walgora mwalgora@cs.cmu.edu